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Our goal was to characterize and understand the large-scale fluctuations in the Kuroshio Extension and its recirculation gyre on times scales from seasonal to interannual. We wished to determine the relationship of the fluctuations to forcing parameters such as surface heat fluxes, wind stress, upstream condition in the Kuroshio and possibly a deep western boundary current. As part of the overall KERE program goals, we sought to understand the dynamics of the Kuroshio Extension in comparison with the Gulf Stream.

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Final Report:
Satellite Observations of the Kuroshio and Kuroshio Extension Region

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1 Long-term Goals

Our goal was to characterize and understand the large-scale fluctuations in the Kuroshio Extension and its recirculation gyre on times scales from seasonal to interannual. We wished to determine the relationship of the fluctuations to forcing parameters such as surface heat fluxes, wind stress, upstream condition in the Kuroshio and possibly a deep western boundary current. As part of the overall KERE program goals, we sought to understand the dynamics of the Kuroshio Extension in comparison with the Gulf Stream.

2 Approach

We used direct analyses of data, a numerical model, and assimilation into a numerical mixed layer model to study the boundary current fluctuations and their relationship to atmospheric variables.

The upper ocean heat budget was determined by assimilating velocities from the Geosat altimeter and sea surface temperature (SST) from AVHRR into a two-dimensional mixed layer model. Assimilation was done in two steps, using a Kalman filter: the first step updates the estimate of the net surface heat flux, based on the temperature tendency from the data, and the second step updates the SST. Velocities derived from the Geosat altimeter were used in the mixed layer model to study the effects of advection on the upper ocean heat balance. To obtain the mean geostrophic velocity the mean sea surface height was determined from the altimeter data using the simple analytic model of a meandering jet. We extended the synthetic model to include the recirculating flows and constrained their intensities by using historical hydrographic data.

Statistical analyses of atmospheric and oceanic fields were used to study air/sea coupling. In addition, TOPEX/Poseidon data have been used to examine the energetics of the Kuroshio Extension and its recirculation gyre.

A wind-forced reduced gravity numerical model, with Kraus-Turner mixed layer physics, was adapted for the of the Kuroshio Extension region to examine the effects of seasonally varying winds on the strength of the western boundary current.

Finally, we used an optimal averaging algorithm to obtain two-week averages of wind stress from the ERS1 scatterometer data. A one-year time series of these winds was used to force the NRL North Pacific model for comparison with the results using a gridded product from a meteorological model, to determine whether better estimates of the wi nd stress field would produce more realistic ocean circulation.

3 Tasks Completed

Estimates of the time-varying net surface heat flux for the Gulf Stream, using a mixed layer model and assimilating satellite SST and surface geostrophic currents.

Estimate of the mean sea surface height field of the Gulf Stream and its recirculation gyres. This result was used to derive the time-dependent surface flow field in the Gulf Stream.

An analysis of the upper ocean heat budget for the Gulf Stream, using a mixed layer model and assimilating satellite SST and surface geostrophic currents.

A statistical analysis of the coupling of atmospheric and oceanic fields for both the

Kuroshio Extension and the Gulf Stream regions.

TOPEX/Poseidon data for nearly two years have been analyzed for the Kuroshio Extension region.

Two years of wind maps were derived from the ERS1 scatterometer data. The NRL North Pacific model has been forced by both ECMWF and ERS1 scatterometer winds for the year 1992 and the resulting ocean circulation compared.

A wind-forced reduced gravity numerical model, with Kraus-Turner mixed layer physics, has been adapted for the of the Kuroshio Extension region to examine the effects of seasonally varying winds on the strength of the western boundary current.

4 Results

(1) Determining the mean Gulf Stream and its recirculations through combining hydrographic and altimetric data

The altimetric data from the first 2.5-year Geosat Exact Repeat Mission were used to estimate the mean sea surface height (SSH) field in the region of the Gulf Stream and its recirculation gyres. Assuming the instantaneous surface velocity field is composed of an eastward flowing jet and two westward recirculating flows, we used the time-varying surface data from the altimeter to determine the shape of the along-track mean SSH profiles and the historical hydrographic data to constrain the net SSH difference across the Gulf Stream system. The two-dimensional mean SSH field was determined by objectively mapping the mean height profiles along the ascending and descending tracks. The SSH jump across the mean Gulf Stream has a maximum of 1.15m around 65W and drops to an almost constant 0.9m downstream of the New England Seamount Chain (NESC). While the SSH jump associated with the mean northern recirculating flow is mostly uniform, we found that the Gulf Stream's southern recirculation has two local gyres that are separated by the NESC. An attempt was then made to estimate the mean deep circulation in this region by comparing the mean SSH field derived from the altimetry data and the surface dynamic height field based on the historical hydrographic data. Despite the large uncertainties, the mean deep flow pattern thus estimated agrees favorably with the overall circulation pattern from the long-term current meter observations. Like the well-defined northern recirculation gyre, we found that a continuous southward flow exists along 57.5W, which follows closely along the deep layer potential vorticity contours. To the south of the Gulf Stream, the deep circulation consists of two separated recirculation gyres; the recirculation gyre to the east

of the NESC appears to be trapped around the Corner Rise.

(2) Heat flux estimates for the Northwest Atlantic by assimilation of satellite data into a mixed layer model

Satellite-derived temperature and geostrophic velocities were assimilated into a mixed layer model to obtain estimates of the net surface heat flux as the residual of the upper ocean heat budget. The heat budget included eddy diffusion, advection and vertical entrainment. Assimilation using the Kalman filter was done in two steps: first, the temperature tendency of the mixed layer was adjusted, and the error was used to derive a new surface heat flux estimate; second, the mixed layer temperature was adjusted. Experiments performed on the actual data suggested that better heat flux estimates could be obtained by allowing the model to predict the mixed layer depth than by adjusting the depth to a climatological value. A systematic error in the temperature tendency appeared to be due to errors in the estimate of the mean SSH from the altimeter; a partial correction for these errors was computed. The agreement between the time series of spatially averaged heat flux and that obtained from the ECMWF atmospheric model was surprisingly good (Figure 2). The temporally averaged heat flux estimates from the mixed layer model were in good agreement with the Bunker climatological values.

(3) An analysis of the upper ocean heat budget for the Northwest Atlantic Ocean

The assimilation of temperature and altimetric velocity into a numerical model of the upper ocean mixed layer allowed an analysis of the upper ocean heat budget for the western North Atlantic Ocean over the 2.5-year period of the Geosat Exact Repeat Mission (November 1986 – April 1989). The balance of terms varied regionally: south of the Gulf Stream advection was relatively unimportant in the heat budget, and the ocean responded passively to changes in surface flux. Within the Gulf Stream and to the north of it, cooling of the upper ocean by advection was as large as 0.15°C per day for periods of several weeks. An analysis of the advection term showed that cooling by Ekman transport was opposed by warming from the geostrophic currents of the Gulf Stream, with cooling typically stronger by a factor of two, because non-uniform Ekman transport disrupted the normal alignment between isotherms and sea surface height contours. There is a complex ocean-atmosphere coupling in this region: in addition to its increase during strong wind events, warming by geostrophic currents is a function of the strength of the Gulf Stream and its recirculation gyres. Over the 2.5-year period, the winds became progressively stronger, causing an increase in cooling by Ekman transport. Advective cooling was balanced by an increasingly positive surface flux (warming of the ocean by the atmosphere), at the rate of about 20% of the annually averaged surface flux per year. This positive trend in the surface flux was also observed in the estimates from the atmospheric general circulation model of the ECMWF.

(4) Atmosphere/ocean coupling in mid-latitude western boundary currents

To determine the nature of the coupling in mid-latitude western boundary currents, oceanographic fields derived from the Geosat altimeter and atmospheric fields from the European Centre for Medium-range Weather Forecasting (ECMWF) were examined for both the western North Pacific Ocean and the western North Atlantic Ocean. Maps of the North Atlantic fields are contained in a data report, along with the estimates of net surface heat flux described in (3) above (Caruso et al., 1995). Despite the short data records, approximately 2.5 years, canonical correlation analyses of fluctuations suggested some clear relationships, which were similar for both oceans. The dominant form of the nonseasonal fluctuations in both oceans was a contraction/elongation of the recirculation gyres, with time scales of 6–9 months. Wind stress fluctuations were clearly correlated with the gyre fluctuations in each ocean, and the fluctuations in the path of the jet were correlated with fluctuations in the wind stress curl (Figure 1). Although, as expected, net surface heat flux and wind stress were correlated, there was no clear correlation between surface flux from ECMWF and the gyre fluctuations.

An independent estimate of the surface heat flux for the North Atlantic, which was obtained by assimilating sea surface temperature into a mixed layer model, showed a clear correlation with gyre changes east of 60°W, which suggests that this aspect of air/sea coupling may be missing in the ECMWF model. The effect of changes in the intensity of the Gulf Stream on the upper ocean heat budget was found to be smaller by a factor of two than the effect of Ekman transport. Thus, it is more likely that surface fluxes play a role in generating the observed ocean fluctuations than that the current fluctuations alter the net surface heat fluxes.

(5) Energetics of the Kuroshio Extension using data from TOPEX/POSEIDON

Altimetry data from the first two-year TOPEX mission were analyzed to investigate the sea surface height (SSH) fluctuations in the Kuroshio Extension and its southern recirculation gyre regions (136°E–180°, 25°N–40°N). To separate the time-dependent (SSH) signals associated with the Kuroshio Extension from those associated with the westward recirculating flows and to study the energetics of these currents, we first estimated the mean SSH profiles along individual groundtracks by assuming the velocity profile of the Kuroshio Extension to be Gaussian-shaped and by successively fitting the synthetic current's height profile to the time-dependent SSH data. The mean SSH field including the influence from the recirculating flows is then derived through the constraint from climatological hydrographic data.

During the two-year period of the TOPEX mission, the eddy kinetic energy (EKE) of

the Kuroshio Extension had relatively uniform values within three separate stages, each of which lasted longer than 6 months. A significant drop in the EKE level is found after the end of 1993. In contrast, the EKE level in the southern recirculation region increased steadily over the two-year period. The energetics analysis shows that this EKE increase in the southern recirculation region is due to the energy transfers from the mean flow field to the eddy field through barotropic instabilities. This barotropic eddy processes are found to be less important for the EKE changes in the Kuroshio Extension and its northern areas. On both seasonal and interannual time scales, the large-scale path fluctuations of the Kuroshio Extension are found to correlate significantly with the surface transport fluctuations: a more northerly Kuroshio Extension tends to correspond to a larger surface transport. Over the two-year period, both the eastward-flowing Kuroshio Extension and the westward recirculating flows weakened steadily. This decline in the intensity of the recirculation gyre is related to the energy transfers from the mean flow field to the eddy field occurring in the region south of the Kuroshio Extension.

(6) Wind and wind stress maps for the North Pacific from the ERS1 scatterometer data

Two years of ERS1 scatterometer winds for the North Pacific Ocean were analyzed to produce 0.5 degree by 0.5 degree biweekly wind maps between 20 S and 62 N, 109 E to 75 W. These maps were produced using a suboptimal temporal interpolation technique and were spatially interpolated using a weighted biharmonic spline. Error estimates were typically about 1.5 m/s for the biweekly averages. Analysis of the curl of biweekly wind maps from ERS1 and ECMWF in the Kuroshio Extension Region show generally good large-scale agreement. Comparisons with NODC operational buoys show that the errors are typically within the 1.5 m/s estimated errors of the biweekly wind maps. However, there is a 5 degree latitude discrepancy in the location of the zero wind-stress-curl line between the ECMWF and the scatterometer wind fields north of the Kuroshio Extension.

(7) Wind forcing in the North Pacific using ECMWF and ERS1 scatterometer data in the NRL numerical model

One year of the ERS1 derived biweekly wind estimates and ECMWF 1000mb biweekly averaged winds, scaled to Hellerman and Rosenstein energy levels, were used as input to the NRL 1/8 degree layered model of the North Pacific Ocean. The model was forced with one year cyclic winds until equilibrium was reached. Significant differences in the model's response were found, particularly in the western tropical Pacific Ocean and the northeastern Pacific Ocean. Figure 2 shows the free surface deviation along 137 E from the model at equilibrium for the ERS1 winds and ECMWF winds compared with mean dynamic height profiles obtained from biannual hydrographic surveys by the Japan Meteorological Agency (Qiu and Joyce, 1992) for ENSO and non-ENSO years. This figure shows that the model

run with ERS1 winds produces a better estimate of the strength and location of the North Equatorial Current and North Equatorial Counter Current (the period modeled, 1992-1993, was during an ENSO event).

(8) Modeling wind-forced seasonal fluctuations in the Kuroshio Extension

Using a reduced gravity model of the North Pacific, we focused on the seasonal fluctuations in the Kuroshio Extension and its recirculation gyre regions due to the surface wind. Figure 3 shows the zonal velocity anomalies in the band from 30N to 40N as a function of time. The values are averaged along the Kuroshio Extension between 140E to 170E. Notice that the eastward Kuroshio Extension (in the band from 34.5N to 36N) tends to intensify in late fall and to weaken in spring. South of the Kuroshio Extension, the seasonal signal is opposite, implying a weakening (strengthening) of the southern recirculation gyre in spring (fall). This modeled result agrees with the observed seasonal signals in the Kuroshio Extension and its recirculation gyre regions (Qiu et al., 1991; Qiu, 1995). Figure 4 shows the upper layer thickness differences between March and September (September - March). There is a wide range of negative upper layer thickness anomalies along the Japan coast extending offshoreward north of the Kuroshio Extension. Over the recirculation gyre region there is a positive anomaly. Both of these anomalies work to increase the eastward transport of the Kuroshio Extension. The seasonal wind patterns suggest that the strong westerlies associated with the Aleutian Low in winter are likely to cause the sea level increase along the Japan coast and north of the Kuroshio Extension, leading to a weaker eastward transport of the boundary jet. At present, we are extending our model studies to separate the regional seasonal wind forcing from the remote ones and to estimate the effect due to seasonal buoyancy input. By evaluating external forcings individually, we hope to clarify the mechanisms responsible for the observed low-frequency fluctuations of the Kuroshio Extension system.

5 Impact for Science

The analysis of the heat budget for the Gulf Stream corroborated the conclusion from the previous Kuroshio Extension analysis, that advection is important in the upper ocean heat balance of the western boundary current regions. However, in the Gulf Stream region, the most important aspect of the advection was due to Ekman transport, whereas in the Kuroshio Extension region, advection by the recirculation gyre was more important.

The analysis of coupling for both western boundary current regions suggested that local winds are clearly coupled with fluctuations in the recirculation gyres. The lack of coupling with heat flux suggests that the ECMWF estimates lack relevant spatial structure.

The energetics analysis of the Kuroshio Extension shows that an eddy kinetic energy increase in the southern recirculation region is due to the energy transfers from the mean flow field through barotropic instabilities. As in the Geosat altimeter analysis, there is a predictable relationship between path and current strength: a more northerly Kuroshio Extension corresponds to a larger surface transport.

Modeling efforts in the Kuroshio Extension region suggest that the seasonal patterns in boundary current upper layer transport, consistent with altimetric observations, can be produced by wind forcing alone.

The comparisons of the NRL model forced by ECMWF and scatterometer winds suggest that systematic large-scale errors in the ocean circulation models can be corrected by the use of more accurate wind fields from the scatterometer.

6 Transitions

Wind maps from the ERS1 scatterometer were sent to Dr. H. Hurlburt at NRL, Stennis Space Center are being used to force the high-resolution North Pacific model in order to compare the results with those using ECMWF winds.

Our result on the variability of the Kuroshio Extension during the Geosat ERM period (Qiu et al. 1991) has been used by the NRL scientists (Dr. H. Hurlburt) in conjunction with their numerical studies on the Kuroshio Extension.

Our result from the altimetric data analysis for the Gulf Stream region was used by Dr. Z. Hallock at the NRL, Stennis Space Center, for comparisons with his IES measurements.

We are working with E. J. Metzger and H. Hurlburt of the Naval Research Laboratory, Stennis Space Center, to compare ERS1 scatterometer and ECMWF wind forcing in the NRL 1/8 degree layered model of the North Pacific Ocean.

7 References:

Caruso, M. C., S. Singh, K. A. Kelly and B. Qiu, Monthly atmospheric and oceanographic surface fields for the western North Atlantic: October, 1986 - April, 1989. Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-95-05, August 1995.

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Qiu, B., K. A. Kelly, and T. M. Joyce, 1991. Mean circulation and variability of the Kuroshio Extension from Geosat altimetry data. *J. Geophys. Res.*, *96*, 18,491–18,507.

Qiu, B., 1995. Variability and energetics of the Kuroshio Extension and its recirculation gyre from the two-year TOPEX mission, *J. Geophys. Res.*,**25**, 2374-2390.

8 Publications resulting from this ONR contract

Qiu, B., K. A. Kelly, 1993. Upper-ocean heat balance in the Kuroshio Extension region, *J. Phys. Oceanogr.*, **23**, 2027–2041.

Qiu, B., 1994. Determining the mean Gulf Stream and its recirculations through combining hydrographic and altimetric data, *J. Geophys. Res.*, **99**, 951-962.

Qiu, B., 1995. Variability and energetics of the Kuroshio Extension and its recirculation gyre from the two-year TOPEX mission, *J. Geophys. Res.*,**25**, 2374-2390.

Kelly, K. A., and B. Qiu, 1995. Heat flux estimates for the North Atlantic, Part I: assimilation of satellite data into a mixed layer model, *J. Phys. Oceanogr.*, **25** (10), 2344–2360.

Kelly, K. A., and B. Qiu, 1995. Heat flux estimates for the North Atlantic, Part II: the upper ocean heat budget, *J. Phys. Oceanogr.*, **25** (10), 2361–2373.

Kelly, K. A., M. J. Caruso, S. Singh and B. Qiu, 1995. Observations of atmosphere/ocean coupling in western boundary currents, *J. Geophys. Res.*, in press.

Huang, R. X., and B. Qiu, 1994. Three-demensional structure of the wind- driven circulation in the subtropical North Pacific, *J. Phys. Oceanogr.*, **24**, 1608–1622.

Caruso, M. J., and K. A. Kelly, 1994. Biweekly wind maps for the North Pacific Ocean from the ERS1 Scatterometer, WHOI Technical Report, in preparation.

Caruso, M. J., K. A. Kelly, E. J. Metzger, H. Hurlburt, Comparison of ERS1 scatterometer and ECMWF wind forcing of an eddy-resolving model of the North Pacific Ocean, in preparation.

9 Presentations resulting from this contract

Qiu, B., and K. A. Kelly, On the variability and the heat balance of the Kuroshio Extension. Spring Conference of the Oceanographic Society of Japan, Tokyo. April, 1993.

Qiu, B., and K. A. Kelly, Upper ocean heat balance in the Kuroshio Extension region. KERE project meeting at Naval Research Laboratory, Stennis Space Center, Mississippi, May, 1993.

Kelly, K. A. and B. Qiu, Heat flux estimates in the Gulf Stream region using satellite altimetric data and sea surface temperature, Satellite Altimetry and the Oceans, Toulouse, France, Dec. 1993.

Kelly, K. A. and B. Qiu, Heat flux estimates in the Gulf Stream region using satellite altimetric data and sea surface temperature, Ocean Sciences Meeting, San Diego, Feb. 1994.

Kelly, K. A., H. E. Hurlburt, M. J. Caruso, and E. J. Metzger, Comparison of the NRL North Pacific model results using ERS1 scatterometer and ECMWF winds, NSCAT Science Working Team meeting (proceedings), June 1–3, 1994.

Kelly, K. A., and B. Qiu, The role of the Gulf Stream in ocean to atmosphere heat fluxes, in The Atlantic Climate Change Program (proceedings), May 9–11, 1994.

Kelly, K. A., The upper ocean heat budget in the Northwest Atlantic, seminar at University of Hawaii at Manoa, May, 1994.

Kelly, K. A., The upper ocean heat budget in the Northwest Atlantic in the Northwest Atlantic from satellite altimetry and sea surface temperature, invited talk at Spring AGU Meeting, Baltimore, May, 1994.

Kelly, K. A., The upper ocean heat budget in the Northwest Atlantic, seminar at Woods Hole Oceanographic Institution, March, 1994.

Kelly, K. A., Surface heat flux estimates in the Gulf Stream region using satellite data, seminar at Lamont-Doherty Earth Observatory, March, 1994.

Kelly, K. A., Surface heat flux estimates in the Gulf Stream region using satellite data, seminar at University of Maryland, March, 1994.

Kelly, K. A., Atmosphere/ocean coupling in mid-latitude western boundary currents, seminar at Pacific Marine Environmental Laboratory, August, 1994.

Kelly, K. A., Fluctuations in western boundary current recirculation gyres, seminar at Old Dominion University, July, 1994.

Qiu, B., and K. A. Kelly, Variability of the Kuroshio Extension and its recirculations from the TOPEX mission. AGU Fall Meeting, San Fransisco, December, 1994.

Kelly, K. A., M. J. Caruso, S. Singh and B. Qiu, Observations of atmosphere/ocean coupling in mid-latitude western boundary currents, AGU Fall Meeting, San Francisco, December, 1994.

Caruso, M. J., K. A. Kelly, E. J. Metzger, H. Hurlburt, Comparison of ERS1 scatterometer and ECMWF wind forcing in the Kuroshio Extension region, AGU Fall Meeting, San Francisco, December, 1994.

Caruso, M. J., K. A. Kelly, E. J. Metzger, H. Hurlburt, Comparison of ERS1 scatterometer and ECMWF wind forcing of an eddy-resolving model of the North Pacific Ocean, NSCAT Principal Investigators Meeting, Kyoto, Japan, November, 1995.

EEO and Minority Support Documentation

1 Number of female grad students
0 Number of minority grad students
0 Number of Asian grad students
0 Number of female post-docs
0 Number of minority post-docs
0 Number of Asian post-docs

Service

Kelly, K. A., NASA Earth System Science and Applications Advisory Committee, 1994–1995.

Kelly, K. A., NASA Altimeter Study Group, 1994.

Honors/Awards

Outstanding Poster Award, Satellite Altimetry and the Oceans, Toulouse, France, December 1993.

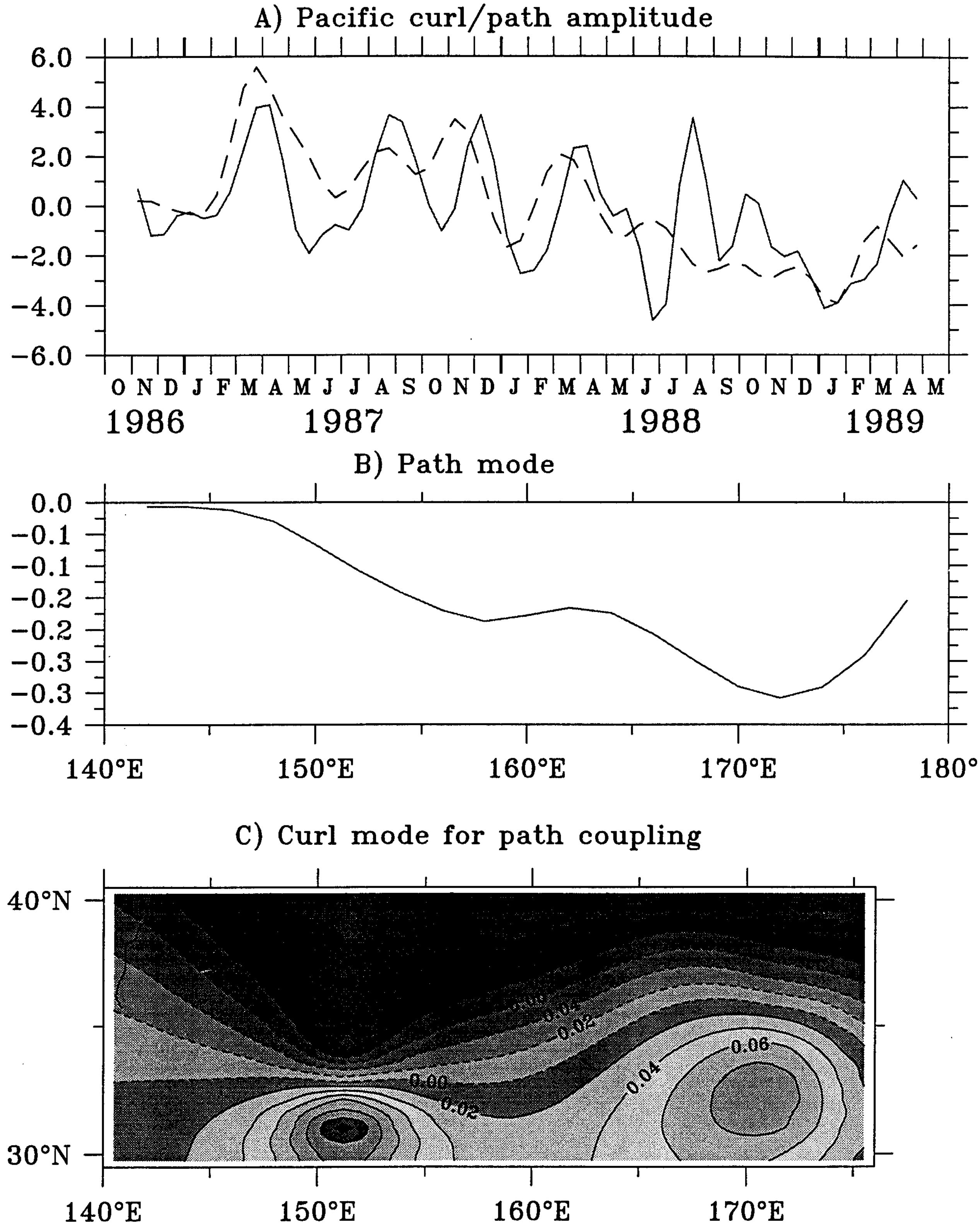
Figure Captions:

Figure 1: Canonical modes of wind stress curl and path in the Kuroshio Extension. (a) Time series for wind stress curl (solid line) and path (dashed line) for mode 1. Note that the wind stress time curl series has been scaled by a factor of 5 $\times 10^6$ for plotting. (b) Spatial mode for path and (c) spatial mode for wind stress curl.

Figure 2: Sea surface height along 137 E from model and data. Mean dynamic height profiles obtained from biannual hydrographic surveys by the Japan Meteorological Agency (Qiu and Joyce, 1992) for (solid line) ENSO and (dashed line) non-ENSO years. Free surface deviation from the NRL model at equilibrium for the (dotted line) ERS1 winds and (dash-dot line) ECMWF winds. The wind fields were from the same time period, which was an ENSO year.

Figure 3: Zonal velocity anomalies as a function of time (m/sec). The values have been averaged along the Kuroshio Extension from 140E to 170E. For clarity, the same seasonal cycle is plotted for a 2-year period. The Kuroshio Extension, located between 34.5N to 36.5N, has a larger eastward transport in fall than in summer. This seasonal signal is reversed south of the Kuroshio Extension in the recirculation gyre region.

Figure 4: Difference in the modeled upper layer thickness between March and September (September - March, in meters).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2.0
0.0
−2.0
−4.0
−6.0
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1986
1987
1988
1989
B) Path mode
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−0.1
−0.1
−0.2
−0.2
−0.3
−0.3
−0.4
140°E
150°E
160°E
170°E
180°
C) Curl mode for path coupling
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0.04
0.02
0.00
140°E
150°E
160°E
170°E

Fig. 1

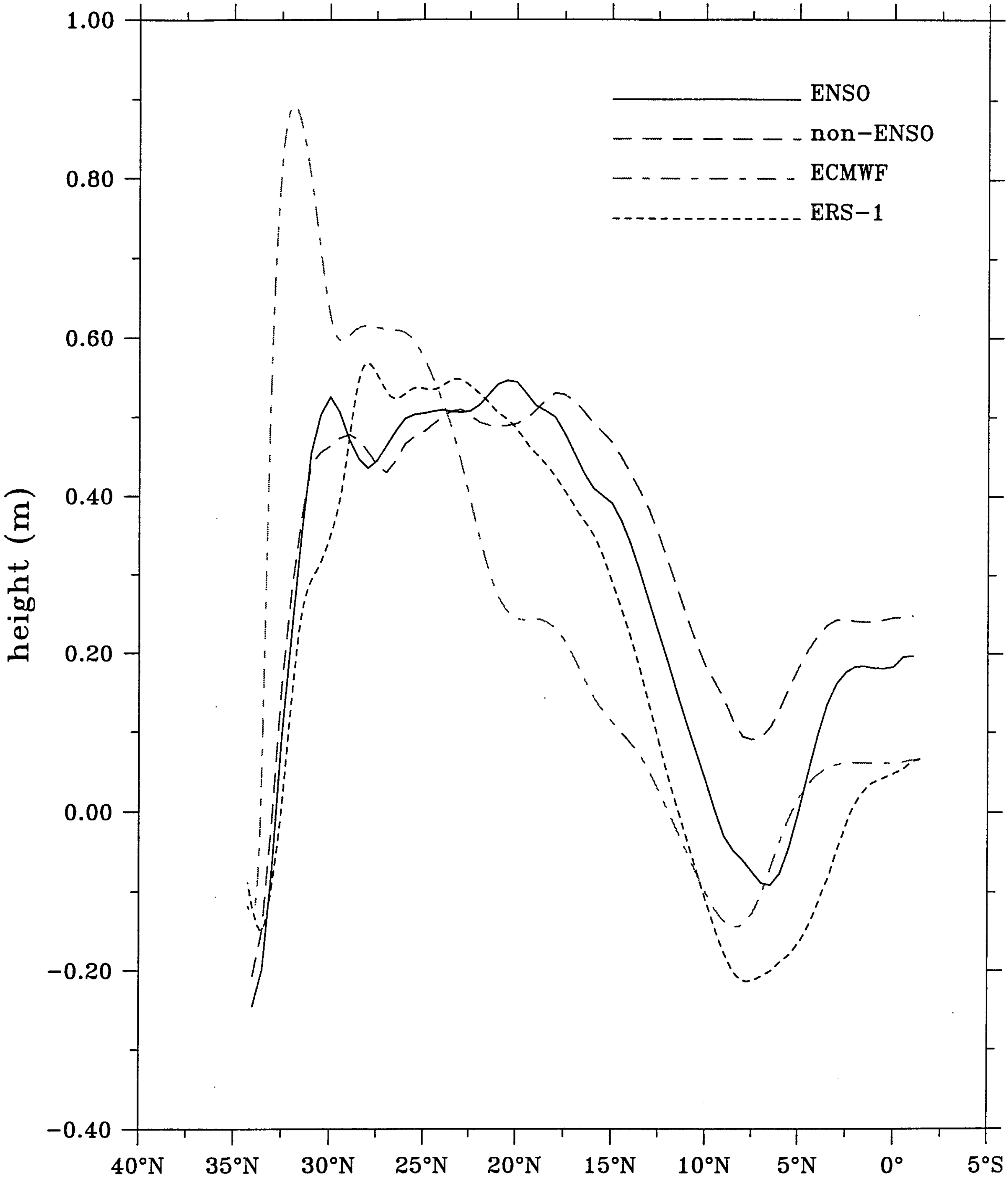
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Fig. 2

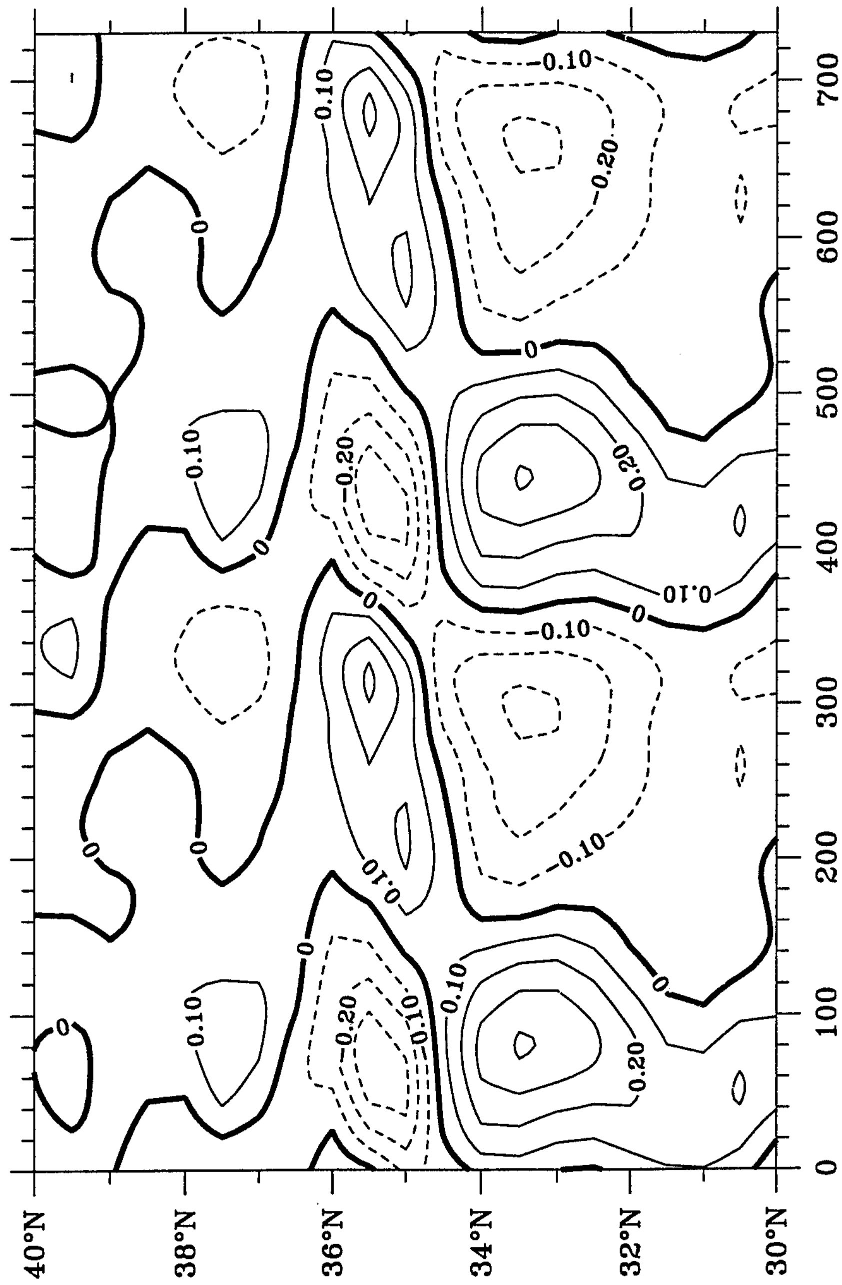
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Fig. 3

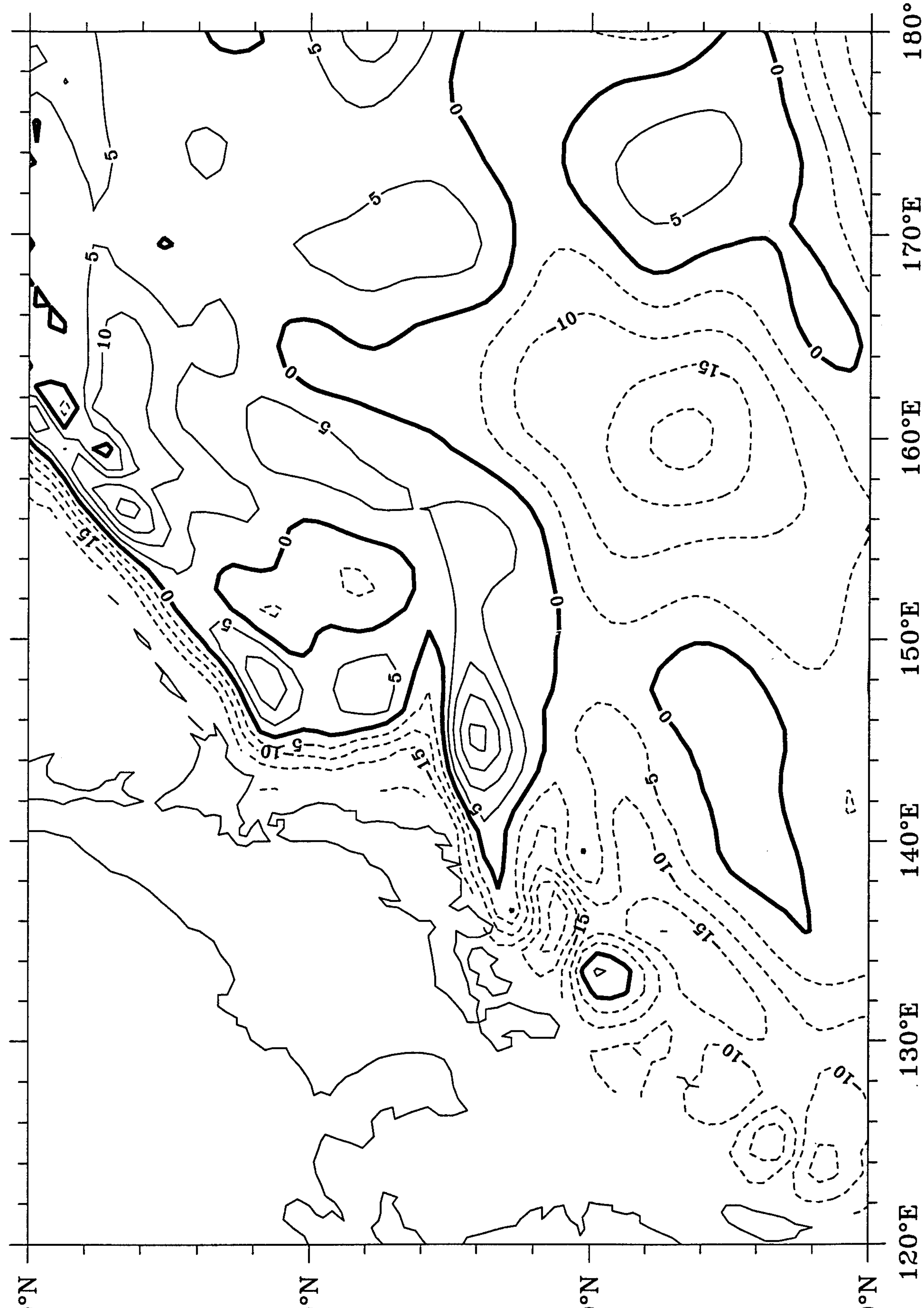

Fig. 4